

## **Power Quality State Estimation: A New Concept**

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## Abstract

The need to modernise the grid to enable it to meet the needs of the future is well accepted. This has led to the Smart Grid concepts as a pathway for increasing the smartness of the electrical grid so as to meet the demands of the future. Part of this involves advances in metering infrastructure which will make a large amount of data available in the future. This necessitates using smart algorithms to take full advantage of the available data so as to improve management of the distribution system. The importance of power quality issues, due to the significant losses associated with poor power quality, has resulted in research being focused on extending the concept of state estimation techniques into power quality issues as well. This paper gives an overview of power quality state estimation and then under the umbrella of Power Quality State Estimation (PQSE) as a smart algorithm, focuses on one the most recent addition, Transient State Estimation (TSE).

## 1. Introduction

Today more than ever before the electricity network is undergoing dramatic change. The push to use more sustainable energy sources and the need for reduced environmental pollution has spurred the interest in renewable energy sources such as wind and photo-voltaic (PV). Better use of infrastructure, the desire to reduce the use of fossil fuels in transportation, and pollution, has elevated the interest in plug-in hybrid vehicles and full electric vehicles as well as load management. Smart Grid has been a buzz word catching the attention of governments and power industry throughout world [1,2]. The term Smart Grid means different things to different people as the perceived benefits, and hence drivers, are different in different countries and even within individual electricity utilities. Regardless of one's concept of a Smart Grid, the need for a reliable two-way communication system is central. Smart Grid is seen as the great enabler for distributed generation (DG) and particularly for renewable resources. The problem of controlling a large number of disperse sources as well as dealing with grid issues due to reversal of power flows in distribution systems (with implications on protection systems) are expected to be overcome by the Smart Grid initiatives. Power Quality (PQ) includes voltage quality, which is a measure of the deviation of the voltage waveform from the ideal sinusoidal waveform (at rated voltage and frequency). The new initiatives, particularly the use of power electronic equipment, have the potential to deteriorate the Power Quality. The size and complexity of modern electrical power networks and the cost of monitoring and telecommunication equipment make it unfeasible to fully monitor the PQ throughout the electrical network. However, with strategically selected measurement locations, estimation techniques can determine the parameters at unmonitored locations. Fundamental frequency state estimation is now a standard tool in modern power systems. This has been extended to Power Quality State Estimation (PQSE) whereby measurements at a limited number of locations are used to identify the location of the source(s) of the disturbances. This is essential to enable remedial action to be taken promptly. This paper provides an overview of the state-of-the-art techniques for

Power Quality State Estimation in a large electrical power system with a focus on Transient State Estimation.

## **2. Existing Smart Algorithms**

There is already a high level of smart algorithms deployed in some electrical power systems, but these are specially schemes designed as one-off to overcome specifically identified problems. These are based on studying numerous contingencies and determining the best course of action. For example in New Zealand there are “run-back schemes”. If a certain contingency occurs then generation in certain locations (or HVDC link) is backed-off to ensure remaining circuits are not overloaded, thereby causing their tripping. Run-back schemes are seen as a way of allowing new generation to connect while limiting or avoiding the need for asset upgrades [3-6].

In the area of condition-based maintenance, if the voltages and currents are monitored, when a circuit breaker has to interrupt a fault (or used for switching) then the duty (stress) on the circuit breaker can be calculated. This information is fed into an algorithm to inform when maintenance is required for the circuit breaker.

With sufficient measurements and suitable instrumentation, on-line estimation of the electrical parameters of overhead lines and cables as well as their temperature can be performed. This information allows better utilisation of assets through dynamic line ratings. It could also allow signatures of equipment to be determined. This would aid detection of incipient problems in equipment such as bushings, CTs, windings, cables, metal oxide surge arresters and circuit breakers, and remedial action taken promptly.

## **3. Power Quality State Estimation**

### **3.1 Introduction**

Power quality, or more specifically voltage quality, is a measure of the deviation of the voltage waveform from the ideal sinusoidal waveform (at rated voltage and frequency) and encompasses such phenomena as:

- steady-state voltage magnitude (under- or over-voltage),
- variations in the peak or RMS voltage (sag and swells),
- harmonics (and inter-harmonics),
- voltage fluctuations (light flicker) and
- transients (spikes, impulses or surges).

The exact way in which power quality is assessed and quantified depends on the particular issue and the potential impact. PQSE is a class of techniques which, despite their different formulation and different quantities used, have the common feature that they are applying state estimation techniques to power quality issues [7]. This is depicted in Fig. 1.

### **3.2 Fundamental frequency state estimation**

Fundamental frequency state estimation is classed as a PQSE technique as it deals with steady-state voltage which is a PQ issue. Because of the abundance of revenue meters the measured quantities are real and reactive power while the state variables are the busbar voltages (magnitude and angle), which results in a nonlinear measurement equation. Due to the number of measurements the problem is over-determined which allows the use of bad data techniques to counter the presence of bad measurements on the estimates.

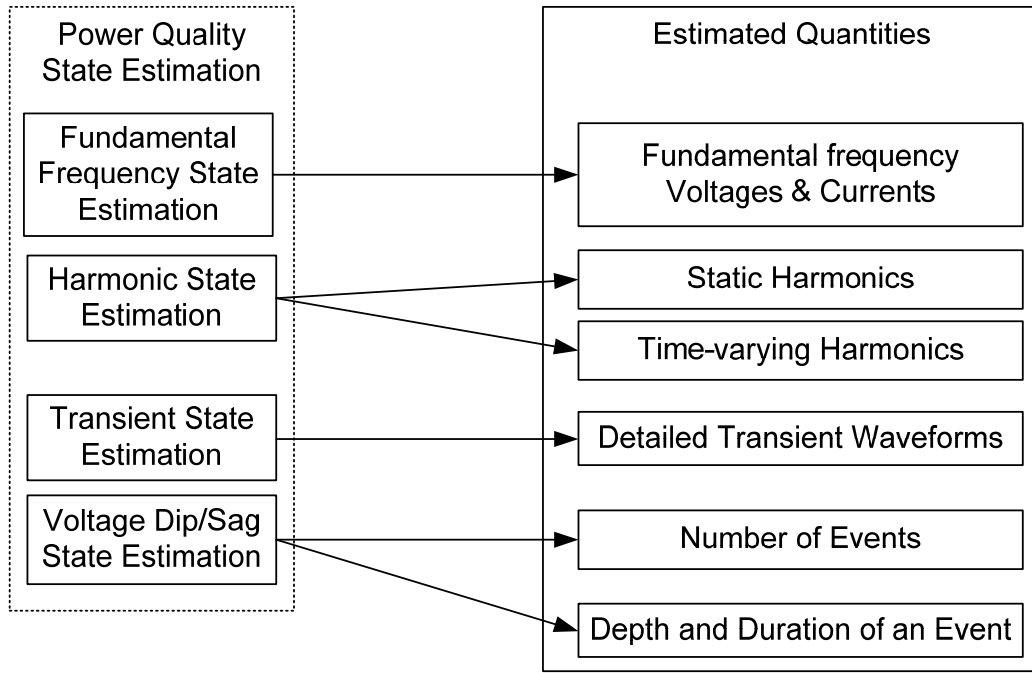


Figure 1. Overview of Power Quality State Estimation

### 3.3 Harmonic State Estimation

Harmonic State Estimation (HSE) techniques estimate the harmonic voltages and currents throughout the system from limited measured harmonic data [8-10]. This is the reverse of harmonic penetration which calculates the harmonic voltages and harmonic currents from knowledge of the harmonic sources and the system topology and system parameters. In HSE the harmonic source locations and magnitude are estimated, along with the harmonic voltages and currents, from a limited number of harmonic measurements. This difference is illustrated in Fig. 2 where the harmonic penetration requires complete knowledge of the network, loads and harmonic sources while HSE utilises harmonic voltage and current measurements to estimate the unknown loads and harmonic sources. Fig. 2 also depicts the Lower South Island of New Zealand test system together with what can be estimated for the given set of measurements.

In HSE harmonic voltages and harmonic currents are measured and the state variables are the phasor harmonic voltages at the busbars, leading to a linear equation of the form:

$$[H]\underline{x} = \underline{z} + \varepsilon \quad (1)$$

Due to the present cost of PQ monitors it is unlikely that the system is over-determined which necessitates the use of Singular Value Decomposition (SVD) as it can solve under-determined systems rather than the traditional Normal equation approach. The SVD algorithm is robust and gives additional information, such as observability, however it is computationally more demanding, which is not an issue if estimating a quasi-steady-state phenomena like harmonics. A great deal of work has been done on HSE from different points of view such as finding the optimal number of the measurements and the best location for them [11], bad data analysis [12], varying harmonic levels with time [13], estimating the type of loads and hence which generate harmonics [14]. Implementation of HSE, based on a field- test data in Japan also has been presented in [15].

The measurement equation (1) is a complex-valued problem therefore early versions converted the measurement equation to a real valued problem for that real-valued SVD routines could be used. This is achieved by expanding (1) to give:

$$\begin{pmatrix} \Re(z) \\ \Im(z) \end{pmatrix} = \begin{bmatrix} \Re(H) & -\Im(H) \\ \Im(H) & \Re(H) \end{bmatrix} \begin{pmatrix} \Re(x) \\ \Im(x) \end{pmatrix} + \begin{pmatrix} \Re(\mathcal{E}) \\ \Im(\mathcal{E}) \end{pmatrix}$$

where  $\Re$  and  $\Im$  represent the real and imaginary part, respectively. This conversion to a real valued problem is no longer needed due to the readily available complex-valued solvers (i.e. complex valued SVD routines).

Another feature of some early HSE formulations was to start with the primitive admittance matrices for each component and use the node-branch connection matrices to form the system nodal admittance matrix. The present approach is to build the system nodal admittance matrix directly. The component parameters are read in, and knowledge of the component type and connections allow the appropriate elements in the system admittance matrix to be adjusted.

Two issues in HSE are the maximum observable subsystem for a given measurement placement, and the minimum cost of instrumentation needed for the observability of a given system. Minimum cost may not be the same as minimum number of measurement channels due to the base cost and incremental cost for additional measurement channels.

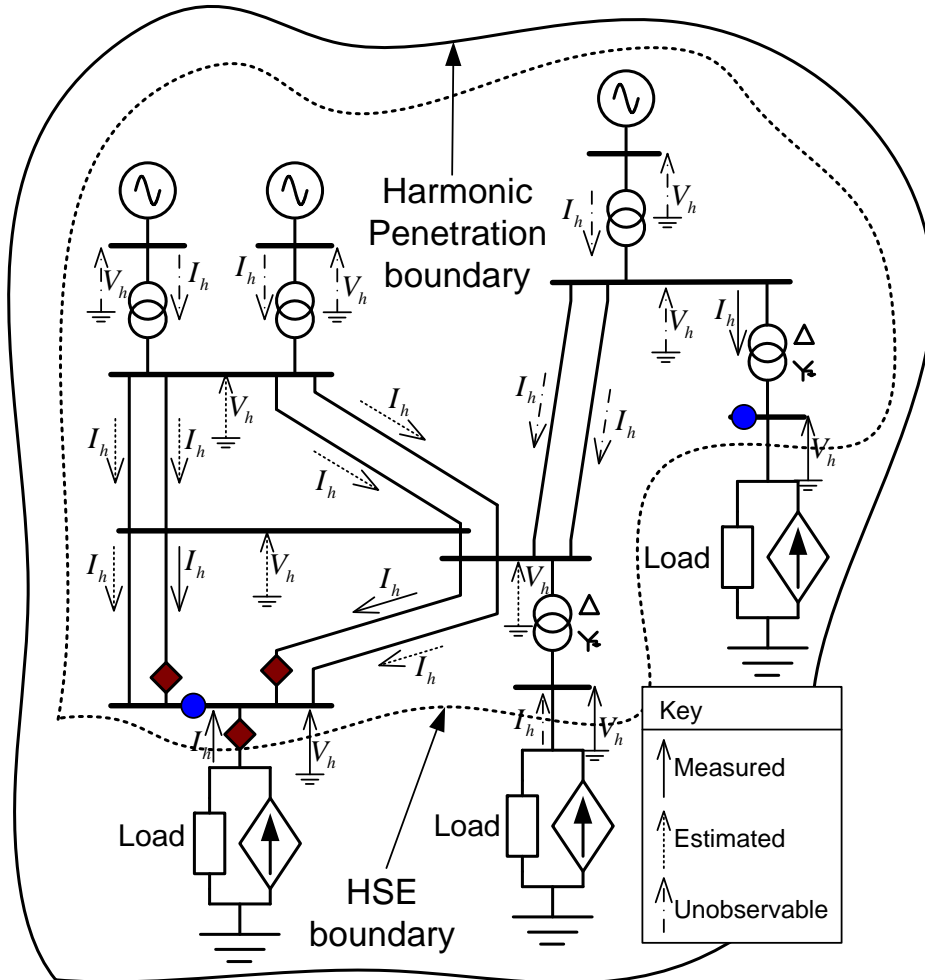


Figure 2. Overview of Power Quality State Estimation

### 3.4 Voltage Sag State Estimation

Voltage Sag State Estimation (VSSE) is generally considered in two main areas. The first area refers to the number of voltage sags arising at unmonitored busbars from the number (frequency) of sags/dips obtained at a limited number of monitored busbars, the second area refers to the use of estimation techniques to measure the sag/dip magnitude and duration at every point on a distribution feeder [16]. This can then be used to calculate power quality indices such as the system Average RMS Frequency Index (SARFIx) [17].

The next contribution in this area optimises the number and location of the PQ monitors for observing a large transmission network in terms of voltage sags, and then deploys it for calculating voltage sag system indices [18].

### 3.5 Transient State Estimation

TSE is a reverse function of transient simulation. Transient simulation is used to analyse the consequences of a disturbance on a power system voltages, currents, etc., TSE is exploited to identify the cause of transient disturbances. Therefore, TSE can be used potentially as a valuable tool for diagnostic purposes in power systems.

Transients necessitate a time-domain solution for the system and hence a dynamic formulation to represent the system and its components. The two broad classes of methods used in the digital simulation of the differential equations representing continuous systems. They are, numerical solution of the differential equations via state-variable approach or converting to difference equations by use of a numerical integrator (i.e. Numerical Integrator Substitution (NIS) or otherwise known as Dommel's method [19-21])

Kent Yu [22-24] introduced the concept of TSE to identify the cause of a transient disturbances by using partial measurements. He used state variable formulation for modelling the system components to develop the measurement equation. However, one contribution [7] showed the possibility of using Numerical Integrator Substitution (NIS), also known as Dommel's method, on a simple single-phase system with lumped components. The NIS approach has many advantages over the state variable formulation.

The test system, shown in Fig. 3, is used to demonstrate TSE. This test system is an 11 kV distribution network taken from Killinchy area, a rural area in South Canterbury, in the South Island of New Zealand. The system consists of a ring of 11kV overhead lines and the lateral outgoing feeders. For illustration purposes symmetrical measurements are arbitrary placed at points indicated in Fig. 3. In practice however, often monitoring the current in two phases is sufficient if there is no zero sequence path. To obtain an overview of the estimation the actual, estimated and difference are plotted in 3-D (see Fig. 4). As this is a three-phase system there are three nodes at each busbar. The most significant difference occurs at nodes 10, 11 & 12, which corresponds to busbar 4, which happens to be unobservable with the chosen measurement points. Busbar 5 is unmonitored, and also the location of the fault. Fig. 5 compares the actual and estimated voltage at this busbar. The accurate estimation clearly shows the ability to estimate the fault location at an unmonitored busbar.

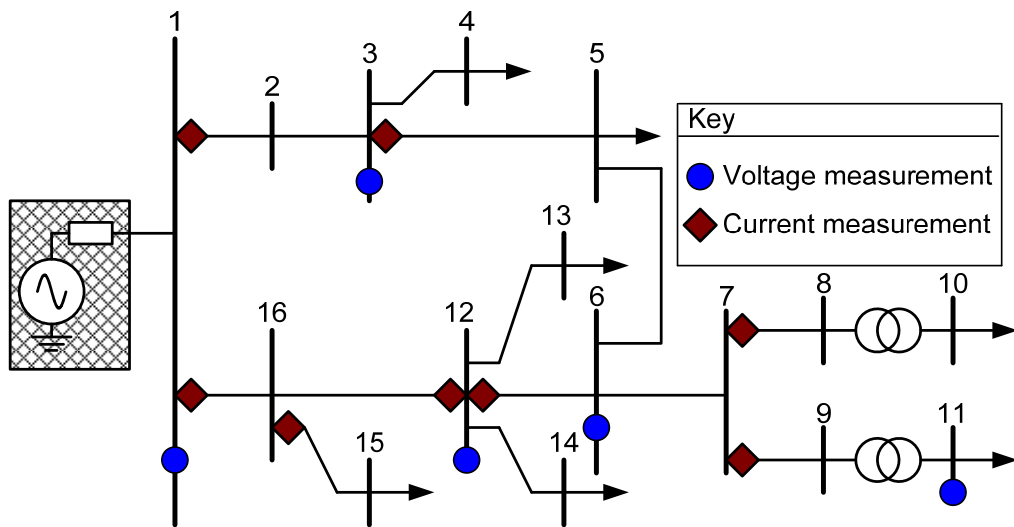


Figure 3. Test System for TSE

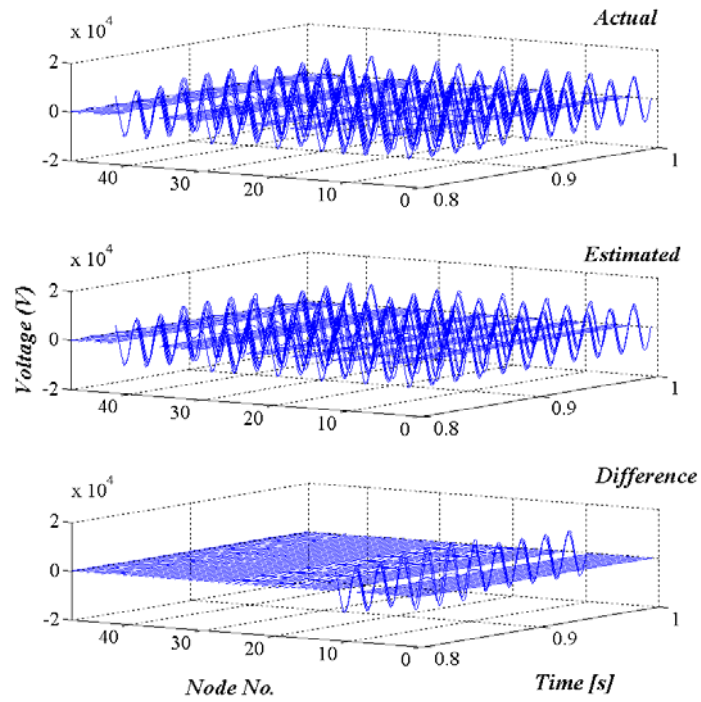


Figure 4. 3-D representation of estimation and actual harmonic voltages

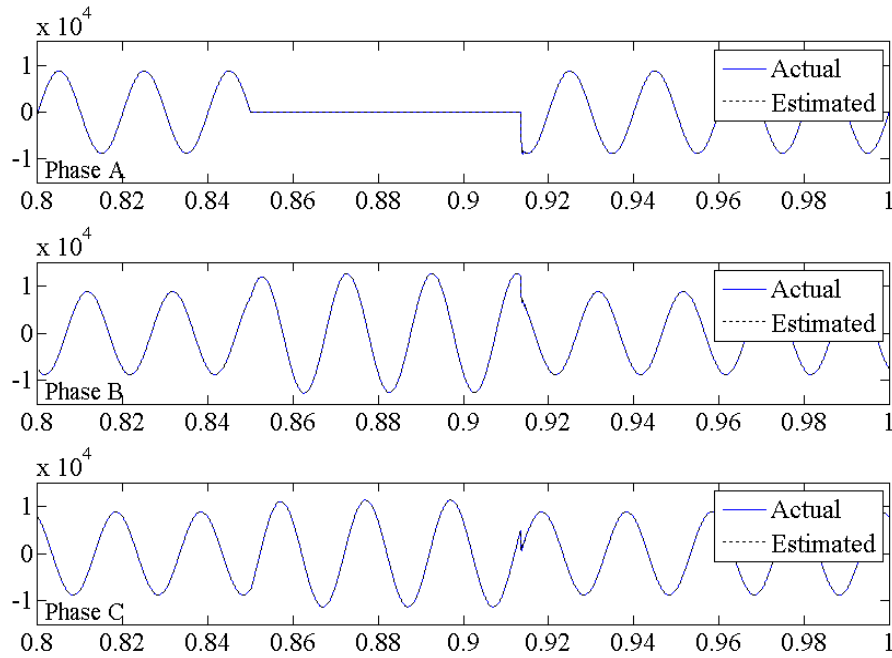


Figure 5. Comparison of Actual and Estimated voltages at busbar 5.

### 3. Conclusions

The transition to the Smart Grid concepts promises an abundant amount of data will be available and this needs to be turned into useful information. This paper has introduced Power Quality State Estimation as a smart algorithm for managing power quality issues. Emphasis has been on Transient State Estimation as this is the newest PQSE technique. TSE is very promising and has been demonstrated to be very accurate, even in the presence of measurement noise, however still a lot of further development is needed on improving the component models before it can be a general purpose tool deployed in SCADA systems.

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